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## IMPACT OF DISTRICT HEATING AND GROUNDWATER HEAT PUMP SYSTEMS ON THE PRIMARY ENERGY NEEDS IN URBAN AREAS

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### ABSTRACT

This work is focused on the planning of rational heating systems for urban areas.

From the sustainability viewpoint, district heating is an important option to supply heat to the users in urban areas. The energy convenience of such option depends on the annual energy request, the population density and the efficiency in heat production. Among the alternative technologies, geothermal heat pumps (both open loop and closed loop heat pumps) play a crucial role.

This paper aims to propose a procedure to select which users in a urban area should be connected with a district heating network and which ones should be heated through an alternative technology, in order to reach a globally optimal system from the energy viewpoint.

The procedure proposes district heating as the initial choice for all the users. The users are then progressively disconnected to the network, according with the primary energy required to supply them heat, and the alternative technology is considered for disconnected users. Here, ground water heat pump is considered as the alternative technology. The total primary energy request is assumed as the objective function to be minimized. To reach this result, the exergetic cost of heat supplied through heat pumps system must be evaluated. Such evaluation is not trivial, as it must include proper analysis of both the district heating network and the alternative system. In the case of densely populated areas, an additional consideration is necessary: the subsurface thermal degradation caused by heat pump installations may affect the performances of surrounding installations. This impact is calculated through a thermo-fluid dynamic model of the subsurface.

The application to an Italian town is considered as a test case. The optimal configuration of the overall urban heating system is obtained. This configuration corresponds to the minimum primary energy request to supply heat to all the users (those connected to the network and those using an alternative heating system).

### INTRODUCTION

District heating is a rational way to supply domestic heating and hot tap water to buildings in densely populated towns, especially in areas with continental climate. District heating networks (DHNs) are generally fed by cogeneration power plants, biomass boilers and other renewable energy systems, industrial processes heat recuperators. These systems are often designed to cover base load in order to operate with high utilization factors and thus reduce the payback period. For this reason, peak loads are covered using boilers.

District heating systems have to compete with distributed cogeneration and heat pumps. These options are particularly interesting in the case of areas with smaller population density, where district heating becomes economically and energetically expensive. In particular, heat pumps have great potential of application [1]. Trade off between technologies depends on various parameters: energy and power density (i.e. energy request and power request per unit ground surface), distance from the potential thermal plant, etc.

Among the available heat pump technologies, groundwater heat pumps have potential advantages in terms of energy efficiency and environmental impact, but performances depend on the technology, heating and cooling load, and characteristics of the aquifer. As an example, Figure 1 shows the effect of inlet water temperature on the coefficient of performance (COP) of a heat pump.

This means that a reduction of 10% of the COP is provoked by reduction of about 2.5 °C in the inlet water temperature. In the case of massive installation in a urban center, it is possible that the water discharged by a heat pump (which is colder than the inlet temperature in winter operation) affects the temperature of water entering a downstream installation. The

latter will be operating with smaller COP than in the case of unperturbed groundwater. The extension of perturbed area mainly depends on water velocity in the ground, as discussed later in the paper.

Moreover, in the case of open loop systems, the potential energy of water is not recovered even if it is re-injected in the ground, thus this quantity affects the energy required for pumping and must be specifically calculated for the considered site.

Most heat pump analyses proposed in the literature are focused on the evaluation of energy efficiency of heat pump systems or their economic aspects (see for example [2-4]). In [5], the overall system effectiveness is evaluated using a multidisciplinary analysis joining together information from energy analysis of a building and its heating/cooling plant with hydro-geological analysis. The proposed approach uses three different models: 1) a time dependent energy model of the building in order to determine heating and cooling load; 2) an off-design model of the heat pump able to calculate the COP depending on the operating conditions; 3) a CFD model of the aquifers able to describe the impact of the heat pump on the groundwater temperature. Groundwater temperature distribution affects the heat pump efficiency if the perturbed area reaches the extraction well or the extraction well of other heat pumps installed in the surrounding areas.

To analyze the conditions that make district heating or an alternative technology the most rational choice, an optimization technique is applied in this work. The objective consists in determining the optimal mix that minimize the total primary energy request, i.e. what are the users to be connected with the district heating network and what are the users to be heated through alternative systems. The procedure considers district heating as the initial choice for all the users in a town. The optimization involves selection of the users (or groups of users) to be disconnected from the network. For these users, the installation of groundwater heat pumps is considered in order to supply them heat. The selection of users to be disconnected is performed through probabilistic based approach, driven by the total primary energy required to supply heat to each single users, i.e. the total energy cost of heat supplied to each single user. Thermoeconomics is used as a tool for the calculation of this cost. Thermoeconomics allows one to account for the costs due to thermodynamic irreversibilities (pumping, heat losses, etc.) as well as the costs for the installation of the network and to distribute these costs among the users according with rational criteria. In addition, a computational fluid dynamic analysis is conducted in order to show possible impacts of heat pump installations on other surrounding installations.

The Turin district heating network is considered as an application of this procedure. A parametrical analysis is conducted by changing the efficiency of the heat pumps in order to evaluate the effects on the optimal system configuration.

## OBJECTIVE FUNCTION

The optimal synthesis of energy systems is here approached by starting with a superstructure [6], which is a district heating network (DHN) connecting all the possible users to the thermal plant. The use of a superstructure is the most common approach to synthesis problems. Once the superstructure is built, the synthesis problem can be solved as an optimization problem, which is searched through progressive simplification of the initial configuration.

The procedure starts with the evaluation of the objective function in the initial configuration, corresponding to all the users connected with the network. The network is then reduced, through successive elimination of the users characterized by high costs. Pipes connecting these users with the rest of the network are also eliminated. The procedure is stopped when all the users are eliminated.

The details of the optimization procedure are shown by considering the average primary energy consumption of heat provided to the users as the objective function to be minimized. The first step consists then in calculating the productive function in the initial network configuration:

$$\bar{e} = \frac{E_{tot}}{Q_u} = \frac{E_{net} + e_F \cdot Q_F + e_P \cdot L_p}{Q_u} \quad (1)$$

The cost of network  $E_{net}$  is the amount of primary energy per unit of time required to produce the insulated pipes. Components as heat exchangers, pumps, valves have been neglected in the analysis. Primary energy associated with excavation, installation and paving restoration has been also considered. Year is the best unit time to be used for the analysis of such system, because of the seasonal and daily variations of the heat request due to the variations in the external temperature.

Primary energy consumptions corresponding with the main installation labor are shown in Table 1, while the primary energy consumptions required to built network components and for the materials are shown in table 2 [7]. Energy required

for the network installation has been calculated by determining the dimensions of the excavation, which should be 500 mm wider than the pipe external diameter and 650 mm deeper; a sustaining and covering layers of sand 100 mm high is also required [8].

To calculate the energy cost required to build the network, the network must be traced and the diameter of each pipe must be determined. This passes through calculation of the maximum enthalpy flow that the each branch of the network should supply to the users. In the analysis performed for the Turin district heating network users have been grouped together into 96 thermal barycenters. Thermal barycenters represent large users (e.g. hospitals) or groups of buildings. The number of barycenters should be selected as trade-off between result accuracy and time required for design and calculation.

For each barycenter, the required thermal power  $\Phi_i$  (in kW) is evaluated by considering the volume of the buildings  $V_z$ , the temperature difference between design room temperature ( $T_a=20$  °C) and the minimum expected outdoor temperature ( $T_e=-8$  °C in the case of Turin), and the average thermal transmittance of buildings (through walls, windows, floor, etc.). Transmittance also accounts for air infiltration. The thermal transmittance of building can be multiplied for a shape factor defined as the ratio of external surface and building volume; this quantity, here indicated as  $r$ , expresses the volumetric heat losses per unit temperature difference. This value has been measured for several buildings connected with the network; an average value of  $0.9 \text{ W}/(\text{m}^3\text{K})$  can be assumed.

$$\Phi_i = \frac{r \cdot (T_a - T_e) \cdot V_z}{1000} \quad (2)$$

Each pipe must carry the thermal power required to all the users located downstream plus the thermal losses (which in the design process can be considered as a small percentage of the useful thermal power, e.g. 3%). This flow is related to the mass flow rate in each pipe through the following equation:

$$\Phi = G \cdot (h_o - h_r) \quad (3)$$

where  $\Phi$  is the thermal flow in the pipe,  $G$  the water mass flow rate,  $h_o$  and  $h_r$  the enthalpies of fluid supplied to the users and returning from the users. These enthalpies are calculated in the case of the Turin district heating network considering a supply temperature of  $120$  °C and a returning temperature of  $65$  °C. The diameter is determined by imposing the maximum velocity  $v_{\max}$  allowed in the pipes. This value is mainly defined on the basis of economic criterion, since friction losses and thus pumping cost depend on the square of velocity, but also on the basis of a stress analysis. On the other hand, a too low velocity would determine a large pipe diameter, thus high investment costs. In this analysis a value of  $2.5 \text{ m/s}$  is considered. The water mass flow rate  $G$  is expressed as:

$$G = \rho \frac{\pi D_{\text{int}}^2}{4} v_{\max} \quad (4)$$

This design calculation must be repeated each iteration. In fact, the number of users decreases with the iterations and so the heat flux to be supplied. This also means that diameters change (the pipes associated to the disconnected users disappear) and the energy cost of the network reduces.

The quantity  $e_F$  in equation (1) is the exergetic unit cost of heat, i.e. the amount of fuel required to produce heat. At the first iteration this term only accounts for heat produced by the power plant and supplied to the network. This is obtained considering the contributions due to the cogenerative combined cycle and the additional boilers. In the case of the combined cycle the primary energy associated to heat production is obtained starting from the efficiency of the plant in pure electricity production (58%). When the plant operates in cogeneration mode, the electricity production reduces because of the steam extraction. The cost of heat is then calculated as the amount of fuel associated to the non produced electricity. This energy cost is  $0.44 \text{ kWh/kWh}$ . Nevertheless, it must be considered that the cogeneration plant is not sized to supply the maximum thermal power required by the network.

The remaining part is supplied by conventional boilers. Figure 2 shows the cumulative heat requirement of the users connected with Turin district heating network. The area below the red curve corresponds to the heat supplied by the cogeneration plant [9]. This is about 80% of the annual energy request. Thus, the quantity  $e_F$  should also consider that 20% of the heat is produced with higher energy cost, about  $1.11 \text{ kWh/kWh}$  in the case of boilers with 90% efficiency.

While the iterations proceed, the cost of heat supplied to the disconnected users must be evaluated considering the cost of heat produced using the alternative energy system (heat pump). Concerning the cost of heat supplied to the connected

users, this is assumed as constant. The reason is that the thermal plant is designed together with the network, thus, the size of combined cycle and boilers depends on the thermal request. Therefore it is possible to consider that the combined cycle always supplies 80% of the annual thermal energy.

As already mentioned, the heat request  $Q_u$  and heat supplied by the thermal plant  $Q_F$  differ because of heat losses  $Q_L$ . Heat losses have been calculated separately for each pipe:

$$Q_L = \pi \cdot D \cdot L \cdot k \cdot (\bar{T} - T_g) \cdot t \quad (5)$$

where  $k$  is the overall heat transfer coefficient and  $\bar{T}$  is the average temperature between supply and return network, while  $T_g$  is the ground temperature and  $t$  is time period (a year).

The last term on numerator of equation (1) accounts for the primary energy required for pumping, being  $e_p$  the exergetic unit cost of electricity and  $L_p$  is the annual electricity consumption, calculated as:

$$L_p = \frac{1}{\eta_{p, year}} \int G \cdot v \cdot \Delta p \cdot dt \quad (6)$$

where  $\eta_p$  is the pump efficiency,  $G$  the water mass flow rate,  $v$  the water specific volume (constant) and  $\Delta p$  the total pressure losses due to pipe friction and localized resistances.

The annual heat load of each single zone  $Q_z$  is calculated by considering, for the whole heating season, the daily difference between the internal temperature and the external temperature, the number of daily heating hours (hh) and the average thermal transmittance of buildings:

$$Q_z = \frac{r \cdot DD \cdot hh \cdot V_z}{1000} \quad (7)$$

where  $DD$  is the degree day of the town, i.e. the summation of daily difference between internal and external temperature, calculated for the entire heating season. For the town of Turin,  $DD$  is 2014 °C, being the heating season from the middle of October to the middle of April, while the number of heating hours per day is 12 per day (this is the value established by the law for users heated with domestic boilers).

The total heat load is calculated as the summation of the contributions of all zones. The network operates for longer time than specified, mainly due to four causes: 1) non contemporary request by the users, 2) presence of particular users, like hospitals, that requires heat for more than 14 hours per day and for an extended period, 3) requirement of domestic water, 4) presence of users that requires heat in summer for air conditioning through absorption chillers. For all these reason, the total load calculated through equation (7) has been considered as spread on 18 hours per day in the seasonal heating, moreover the thermal flow outside this period has been assumed non null, but 11% of the maximum thermal flow. This last assumption has been formulated on the basis of experimental data.

A  $COP=4.1$  is considered as the base value for compression cycle heat pumps. This value is associated to a groundwater temperature of 15 °C and heating system temperatures of 45°C/35°C. When inlet temperature reduces, the  $COP$  changes according with the curve shown in Figure 1. When there are multiple heat pump installations, some interferences may occur. These happen if cold water (in winter operation) discharged by an installation propagates through the ground and reaches a downstream installation. In order to calculate this possible effect a computational fluid dynamic model of the subsurface downstream the injection well of a heat pump is used. This model considers the Darcy equation and the energy equation. These are applied to a domain of 650 m long, 80 m large and 80 m deep. This domain is suitable for the specific installation in Turin area, where the unperturbed groundwater flow is characterized by a velocity of about 2 m/day. The simulation refers to the heat pump that can be used for a building of 15000 m<sup>3</sup>, which is a typical building size.

Two different cases are considered as the two extreme options: an unbalanced heat load, i.e. only winter heat request, and a perfectly balanced heat load, i.e. a reversible heat pump with winter request equal to the summer request. Figure 3 shows the temperature distribution in a longitudinal cross section passing through the injection well in the case of unbalanced heat load. In the figure temperature distribution in the ground is plotted at five equally spaced time frames along two heating seasons. The figure shows that there is a thermal plume (temperature always below the undisturbed ground temperature) in the ground that propagates several hundred meters downstream the injection well, which may affect other installations.

In the case of balanced heat load, the thermal plume is reduced thanks to the summer operation. This is shown in Figure 4. The figure shows that there are smaller areas with temperature below the undisturbed ground temperature with respect to the case of unbalanced heat load. In addition, there are areas with temperature above the undisturbed ground temperature, which is beneficial for winter operation of heat pumps.

Information from these figures can be used in order to evaluate the impact produced by the thermal plume on the COP, depending on the position of the downstream installation. In particular, it is possible to calculate the average deviation of the groundwater temperature with respect to the undisturbed groundwater temperature during the heating season. This deviation is represented in Figure 5 for the two cases of unbalanced and balanced heat load. In the case of unbalanced load (blue plain curve on figure 5), the average deviation is about 2.5 °C close to the injection well and becomes about 1.8 °C at about 250 m. The effect on the COP of a reference heat pump (COP=4.1 in the case of feeding with undisturbed groundwater) is a significant reduction (blue dashed curve). The COP is about 3.7 up to 80 m from the injection well and increases to about 3.8 at 250 m. To reach a COP=4 for a downstream installation it is necessary to locate it about 600 m far from the injection well.

In the case of balanced load, the average deviation is about 1.3 °C close to the injection well (red plain curve) and reduces to about 0.6 °C at about 250 m. The COP of a downstream heat pump (red dashed curve) is reduced to about 3.9 if it is installed within 75 m and increases to about 4 in the case of an installation 250 m far from the injection well.

To calculate the primary energy consumption associated to heat pumps, the average electrical efficiency of the Italian plants is considered. This efficiency is 0.46.

The synthesis procedure also requires calculating the cost of heat supplied to each single barycentre. This is obtained through thermoeconomic analysis, as shown in the next paragraph.

## THERMOECONOMIC BASED OPTIMIZATION

A thermoeconomic analysis is then implemented for the designed network, where all the possible users are connected. In particular, a useful approach that can be adopted for this purpose is that proposed by Valero and co-workers in the eighties [10]. One of its main characteristics is the matrix based approach, in particular the use of incidence matrix for expressing the equation of cost conservation. The incidence matrix (see for example [11]) was formulated in the ambit of the graph theory [12], which is widely adopted for the topology definition as well as the fluid dynamic and thermal calculation of distribution networks [13]. The incidence matrix,  $\mathbf{A}$ , is characterised by as many rows as the branches ( $m$ ) and as many columns as the nodes ( $n$ ). The general element  $A_{ij}$  is equal to 1 or -1, respectively if the branch  $j$  is entering or exiting the node  $i$  and 0 in the other cases. The use of the incidence matrix allows one to express the balance equation of the flow of the general extensive quantity  $G_x$  as:

$$\mathbf{A} \cdot \mathbf{G}_x + \mathbf{G}_{x_d} = \mathbf{0} \quad (8)$$

where  $\mathbf{G}_x$  is the vector containing the values assumed by the quantity  $G_x$  in the nodes and  $\mathbf{G}_{x_d}$  is the vector that allows to account for the amount destructed in the branches, if non null. In thermoeconomics, equation (8) allows one writing the exergetic cost balance:

$$\mathbf{A} \cdot \mathbf{Y}^* + \mathbf{Y}_b^* = \mathbf{0} \quad (9)$$

Where  $\mathbf{Y}^*$  is the vector containing the exergetic cost of all the flows, i.e. the unknowns of thermoeconomic analysis.  $\mathbf{Y}_b^*$  contains the exergetic cost rate of the branches (construction and installation costs). It is worth to recall that these costs represent the amount of primary energy required to make the components of the district heating network available. Calculation of all the costs requires the formulation of  $n-m$  auxiliary equations, which are obtained through definition of resources and products of each component, expressed in terms of exergy flows [14]. The auxiliary equations were formulated as four propositions, whose first (P1) is the conservation of cost, expressed by equation (9) [8]. The others are: (P2) in absence of a different evaluation the exergetic unit cost of an exergy flow entering the system from the environment can be assumed equal to its exergy. This preposition is applied to the term  $e_F$ . Here these costs are assumed as equal to the primary energy consumption required for the production of a unity of energy; (P3) in absence of a different evaluation, the unit cost of a lost exergy flow is the same; (P4a) if the fuel of a component is defined as the difference between two exergy flows, the unit cost of these flows is equal; (P4b) if the product of a component is defined as the summation of two or more flows, the unit cost of these flows is the same. This preposition is applied to the pipe bifurcations.



In the case of a DHN the only auxiliary equation to be applied is the assignment of the same unit cost to the flow exiting each bifurcation [15].

The unit cost of a flow  $e_i$  can then be calculated, by dividing the costs for the corresponding exergy flow:

$$c = \frac{Y^*}{Y} \quad (10)$$

Where  $Y^*$  is the exergetic cost of a general flow and  $Y$  its exergy.

At this point, the unit cost for each user, can be calculated. This cost is not the same for all of them because of the different exergy destruction (mainly due to friction) and the pipe cost associated to the different paths joining the thermal plant with the users.

Figure 6 shows the unit cost of heat supplied to all the users at first iteration (i.e. all the users connected). The figure shows that there is one user characterized by a cost over 0.53 kWh/kWh, while the other are smaller. The figure also shows the four terms that compose the unit cost of heat: 1) cost of heat supplied by the thermal plant to the network, 2) cost due to thermal losses, 3) cost due to the network construction and installation and 4) pumping. The first term is the same for all the users (0.499 kWh/kWh), while the other terms depend on the position of the users and their thermal request. Thermal losses contribute on average for 1.3% to the cost of heat supplied. In the case of the user with the highest cost, this term contributes for over 3.1%. The average contribution due to network construction and installation is about 0.6%, while the maximum contribution is over 1.4%. The average contribution of pumping is about 1.2%, while the maximum contribution is about 1.9%.

A basic iterative procedure introduced in a former paper [16] was applied for the economic optimization of the network configuration. Each iteration consisted of three steps: 1) calculation of the unit cost of all the users connected to the actual network configuration; 2) elimination of the user characterized by the highest cost and the corresponding piping joining the user with the rest of network; 3) calculation of the average cost of heat provided to the users in the new structure, without the eliminated user.

The main advantage of such procedure is that large structures characterized by hundreds of users can be easily processed; the computational time is linearly dependent on the number of decision variables, i.e. the number of users. In contrast, a disadvantage is that it does not guarantee the obtainment of the true optimum. In particular this event can occur when several users in different zones of the network are characterized by values of the unit costs close to the unit cost of the user which is highlighted as the one to be eliminated. In such a case, the procedure formerly proposed allows one to obtain a quasi-optimal structure, in general just slightly different from the true optimal one. Here an improved procedure is proposed in order to avoid local optima.

This procedure is based on probabilistic criteria for deactivating the users. The idea is similar to the Simulated Annealing approach.

In Simulated Annealing, energy states are randomly generated. They are compared with the former one  $E_{old}$ : if the new state,  $E_{new}$ , is lower than the old one, then  $E_{new}$  survives. Otherwise, if  $E_{old}$  is lower than  $E_{new}$ , there is still a probability for the system to leave the old state and enter in the new one. This probability is computed as

$$p = \exp\left(-\frac{E_{new} - E_{old}}{K \cdot T}\right) \quad (11)$$

where  $K$  is the Boltzmann constant and  $T$  is the current temperature of the system.  $T$  changes when it is not anymore representative of the state in which the system is. For this change, usually a linear law is adopted. The higher the difference between the two energy configuration, the lower is the probability for the system to enter in the new state, but still that probability is not null. This allows the SA procedures to escape local optima and reach the global one [17].

The SA method could be used to describe phenomena other than the annealing. In those cases,  $K$  and  $T$  are parameters that have to be chosen very carefully.  $T$  gives the information on the state of the system and  $K$  that is a constant that influences the value of  $p$ .

In the method used for the present analysis, exergetic unit cost of all the users is calculated. Once this is done, a probability function  $p$  is assigned to each of user. This probability represents their probability of being deactivated

$$p_j = \exp\left(-\frac{DC_j}{K \cdot T}\right) \quad (12)$$

The term  $DC_j$  stands for the difference between the unit cost of user  $j$  and the calculated average cost of heat.  $K$  is fixed to a constant value and  $T$  is the number of users connected to the network. Index  $j$  is first set to 1, as the users are processed in order of identification;  $p$  is set equal to the probability  $p_j$ . A random number  $x$  is then extracted. If  $x$  is higher than  $p_j$  the user  $j$  is deactivated; otherwise  $p$  is increased by the value  $p_{j+1}$  and  $j$  is set to  $j+1$ ; the test starts again until a value of  $p$  greater than  $x$  is found.

When a zone is deactivated, a new configuration is found, its heat average cost is calculated as well as the unit cost of all the users still connected.  $T$  is diminished of 1 and the procedure starts again. The calculation continues until all the zones are deactivated.

Each iteration consists of four steps: 1) calculation of the heat average cost of the network and of the unit cost of all the connected users; 2) assignment of a probability cost-based function to all the users; 3) extraction of a random number  $x$ ; 4) identification of the zone to be deactivated.

Although it is not a real SA method, deteriorations are allowed as well as improvements: their greater or lesser acceptability is due to probabilities assigned to users, i.e. to their unit cost. Due to the probability function, each time the algorithm can give different results, for this reason more than one run is necessary to find a good configuration.

## RESULTS

The results obtained by applying the proposed procedure to the Turin area connected to the district heating network are shown in figure 7. This figure shows the effects on the unit cost of heat produced through progressive disconnection of users. Each curve corresponds to a different value of the nominal efficiency of heat pumps to be used as alternative system to district heating. The curves refer to the runs that have conducted to the optimal network. The total number of runs that have been performed for each case is 2000. The analysis has been performed by considering the same nominal COP for all the users. In the case of existing buildings, it is possible that the installed heating system is not suitable for the operation with the small temperatures differences required by the heat pump. In these cases it is possible to consider different options: 1) installation of a new heating system that may operate with heat pumps, such as fan coils; 2) reduction of the heat requirements of the buildings through upgrades of the windows or the insulation; 3) assumption of a different value of the primary energy savings associated to the alternative system in that area, i.e. the heat pump is not anymore the alternative system for that group of buildings.

In the base case (COP=4.1), there is a minimum of the specific primary energy consumption obtained by disconnecting 3 barycenters from the network (and heated through heat pumps). These are users with small thermal request, in fact, the average annual request of each of these barycenters is 16 MJ/year, while the average request of the remaining barycenters is 42 MJ/year. In addition, these users are located far from the main thermal plant, as shown in figure 8. In this figure, the 3 disconnected users are highlighted by the curve A. In the figure the main power plant is on the bottom (TP1). The thermal plant TP2 is only equipped with boilers and heat storage tanks, while the plant TP3 is very small and currently not working.

If a smaller COP is considered (e.g. COP=4.0, as considered in the figure), the optimal system is obtained by connecting all the users to the district heating network. If a larger COP is considered, the number of users to be disconnected to the network in order to reach the optimal system increases. In the case of COP=4.2, the number of disconnected users becomes 8. The disconnected users are again far from the main thermal plant, as shown in figure 8. These users are highlighted by the curve B. The average heat request of each disconnected barycentre is 33 MJ/year. In the case of COP=4.3, the number of disconnected users becomes 64. These users are highlighted in figure 8 by the curve C. The average heat request of each disconnected barycentre is about 34 MJ/year, and only the users with larger thermal request remain connected with the network. The average request of barycenters that remain connected is in fact about 60 MJ/year. Nevertheless it must be recalled that in the areas close the city centre, the distance between buildings decreases and the request per unit of surface increases (because buildings are generally taller), thus the impact of subsurface temperature on the COP performances becomes significant. Therefore it is difficult to achieve such high efficiencies for all the heat pumps.

## CONCLUSION

In this paper the energy optimization of a potential users of a district heating network is conducted. The analysis is performed considering groundwater heat pumps as the alternative to supply heat to users that result disconnected to the network in the optimal system configuration. To evaluate possible interferences between heat pump installations, a CFD



model of the ground is considered. This shows that a heat pump may cause reductions in the COP of downstream installations. This effect must be carefully considered in the case of massive heat pump installations.

A probabilistic approach based on the calculation of exergetic cost of heat associated to each single user connected with the network is used.

Results show that when the COP of the heat pump is between 4.0 and 4.25 there is an optimal configuration with a certain number of users connected with the network, being this number increasing with decreasing COP. In the case of smaller COP all the users result as connected with the network in the optimal configuration. When larger values of COP are considered, the number of users connected with the network tends to zero. Nevertheless this is difficult to achieve, mainly because of the large density of buildings in the city centres. This causes significant impact of heat pump operation on the subsurface temperature, and thus on the performances of heat pumps themselves.

In the case of improvements in the electricity generation, which is expected as a consequence of the increased electricity generation from combined cycles, the energy convenience of heat pumps increases, even when smaller COP are considered.

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Consumption	[MJ/m <sup>2</sup> ]
Clipper	3.56
Hammer	4.73
Electricity generator	4.73
Mini excavator	8.29
Excavator	17.79
Terna	14.23
Track	21.35
Pneumatic rammer	2.39
Pavement restoring	23.74
Roller	19.00
Cement mixer	17.79

Table 1. Primary energy consumptions associated with the installation labor

<i>Sand</i>	<i>[MJ/kg]</i>	0.1
<i>Asphalt</i>	<i>[MJ/m<sup>2</sup>]</i>	2.67
<i>Polyurethane</i>	<i>[MJ/kg]</i>	72.1
<i>Steel</i>	<i>[MJ/kg]</i>	34.44
<i>PEHD</i>	<i>[MJ/kg]</i>	84.4

Table 2. Primary energy consumption associated with components and materials

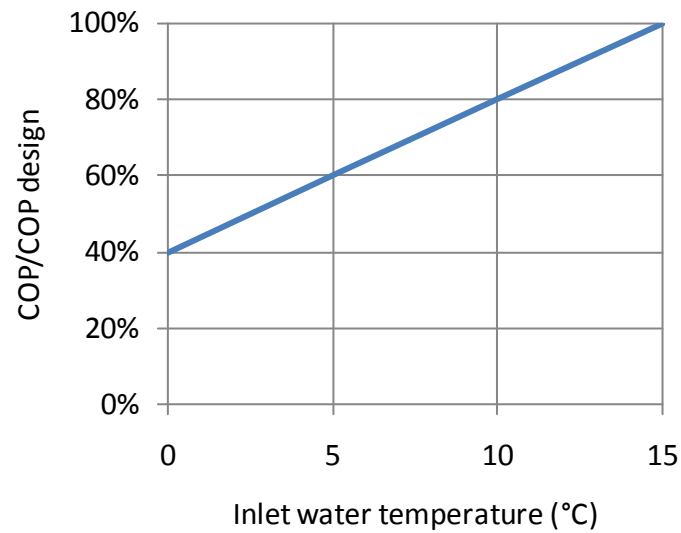


Figure 1. Effect of inlet groundwater temperature on the COP

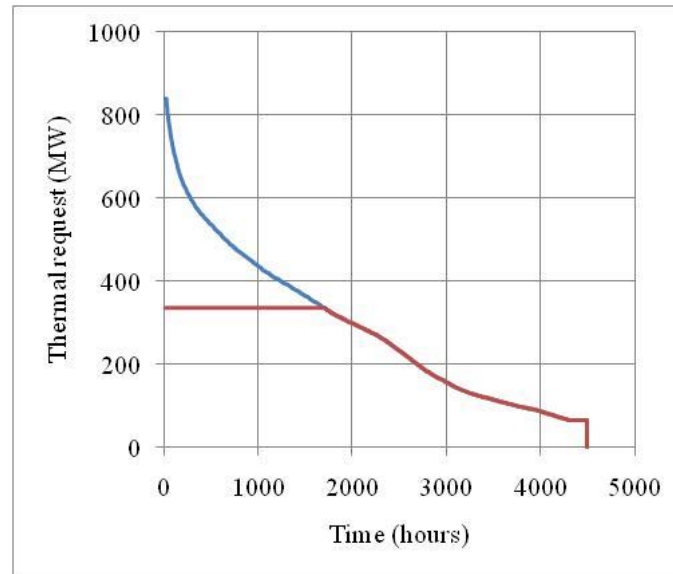


Figure 2. Cumulative heat requirement of the district heating network



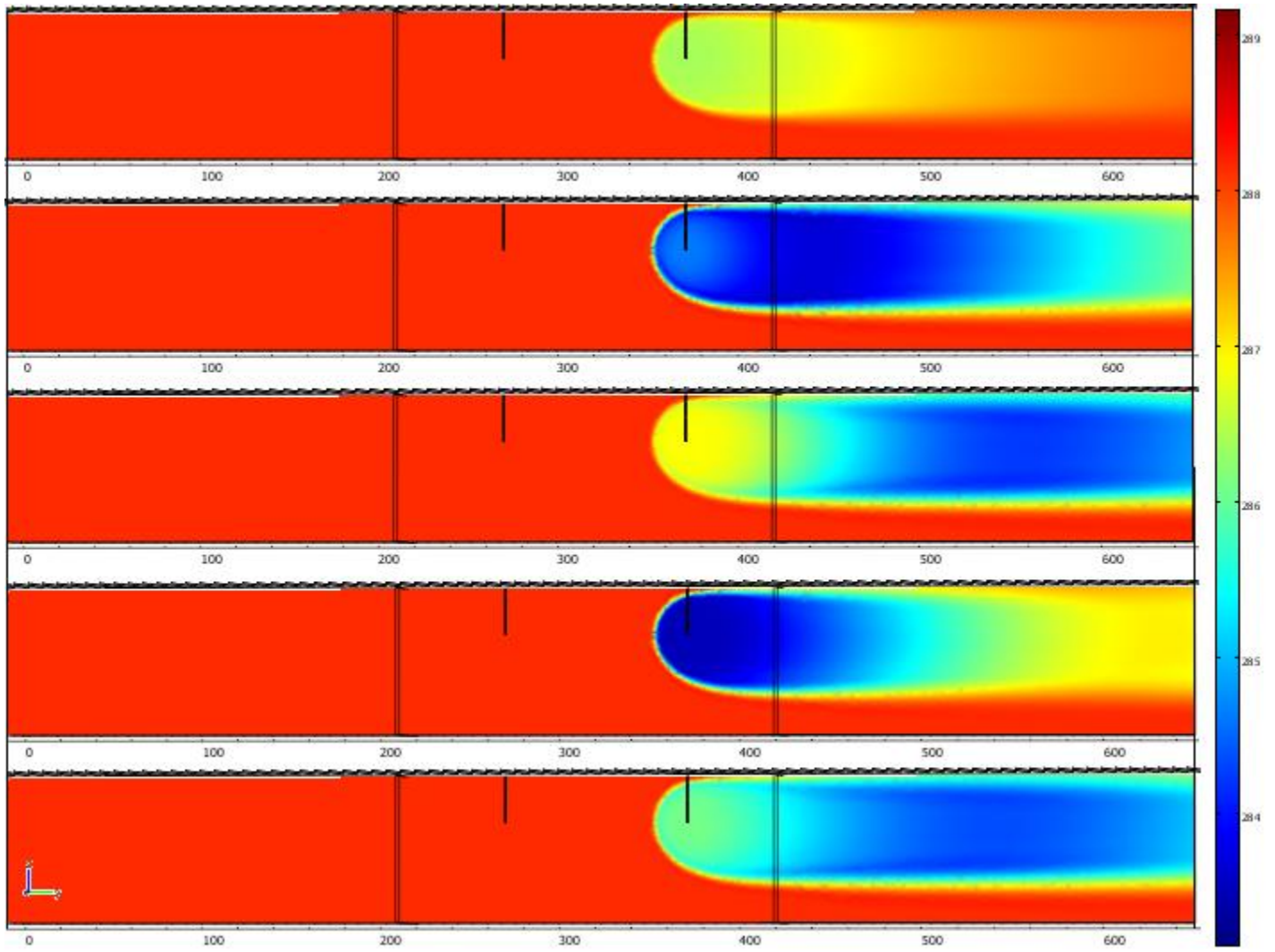


Figure 3. Groundwater temperature distribution for unbalanced heat load

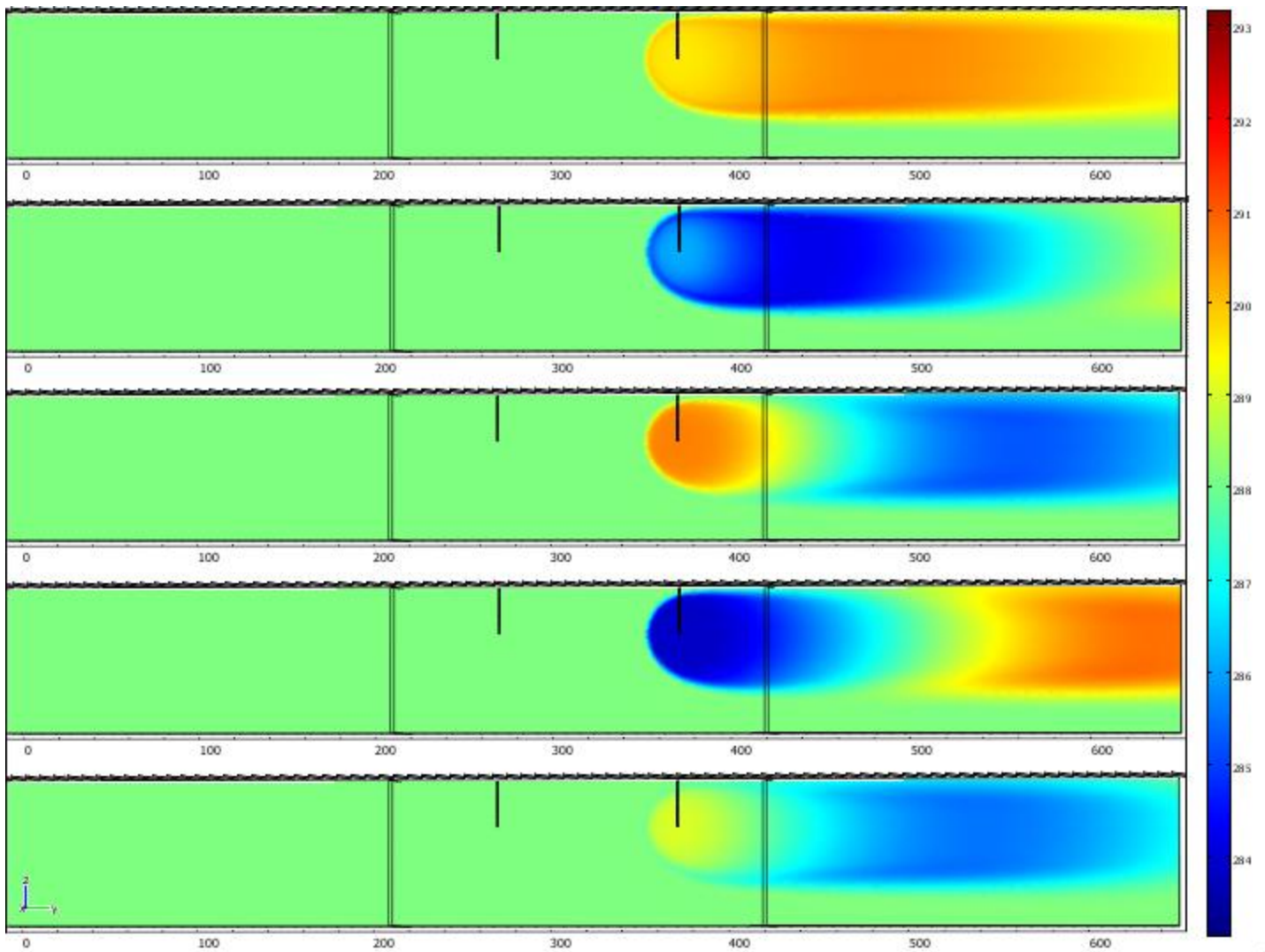


Figure 4. Groundwater temperature distribution for perfectly balanced heat load

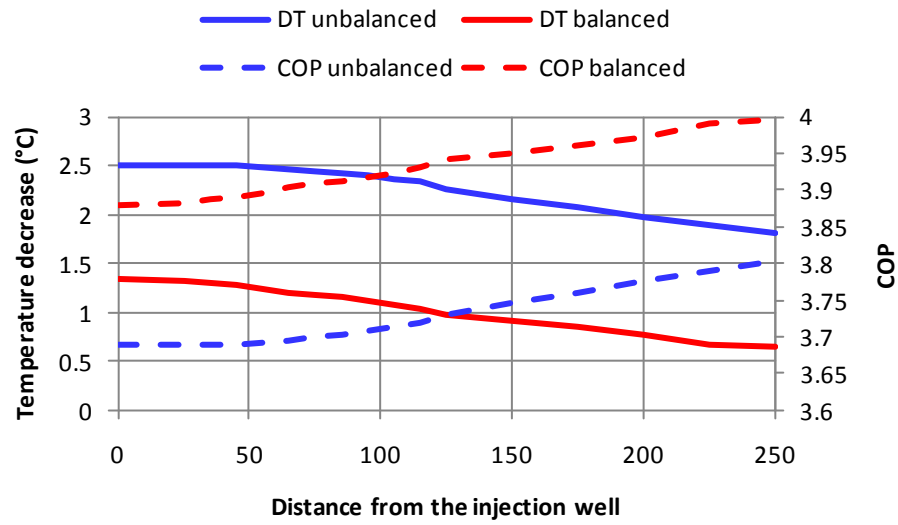


Figure 5. Groundwater temperature deviations and effects on the heat pump COP

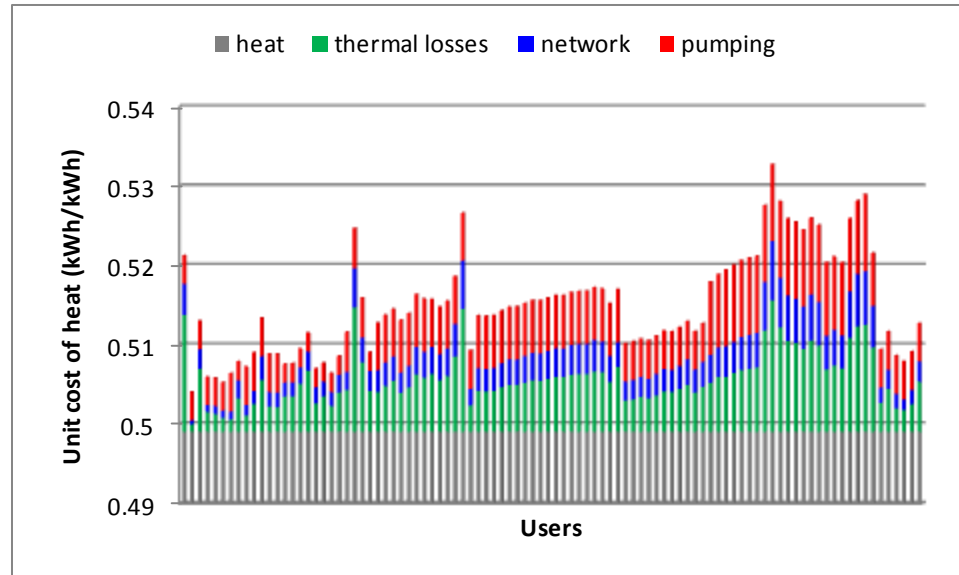


Figure 6. Exergetic unit cost of heat supplied to the users

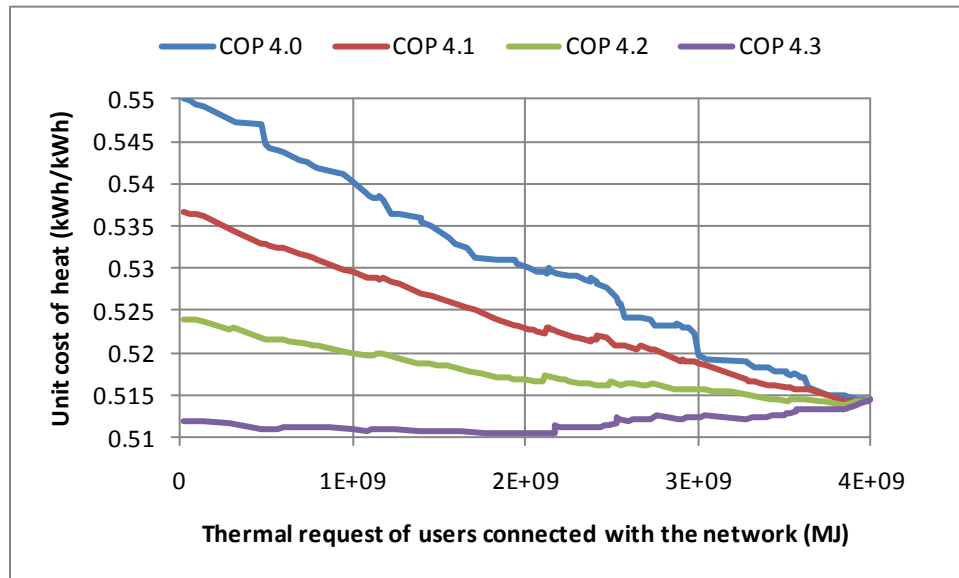


Figure 7. Unit cost (in primary energy per unit of heat) of the heat supplied to the users connected with the network during the optimization procedure

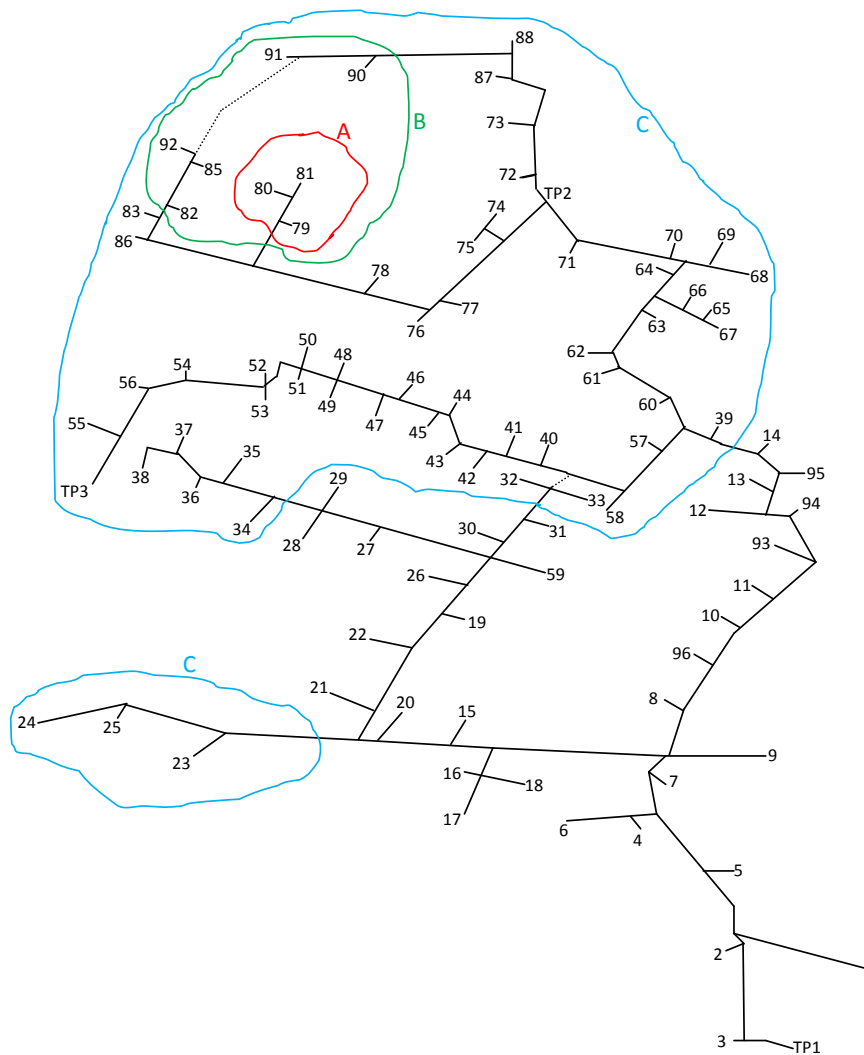


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